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OVER-ALL ECONOMY COMPARISON OF TWO-STAGE CHEMICAL-NUCLEAR AND THREE-STAGE CHEMICAL ORBITAL CARRIER VEHICLES

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OVER-ALL ECONOMY COMPARISON OF TWO-STAGE CHEMICAL-NUCLEAR AND THREE-STAGE CHEMICAL ORBITAL CARRIER VEHICLES

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ABSTRACT

The purpose of this study is to compare the overall economy of transporting large volumes of payload into a typical low altitude orbit using three-stage chemical vehicles and two-stage chemical-nuclear vehicles.

In comparing these two types of transport vehicles, take-off weight and desired annual transport volume are allowed to vary. Vehicles of each type are sized to represent a span of take-off weights yielding a span of payload capabilities. These transporters or orbital carriers are typical of their class and are based on the velocity requirements for a typical low altitude orbit. Operational assumptions, concerning mission reliability and pad time, establish firing rates and launch pad requirements for a given annual transport volume.

The total operating cost can be determined by combining these data with specific cost data on the vehicles, facilities, and operations. The total operating cost can be converted into specific cost in dollars per pound of payload delivered into orbit, and it is this parameter which is used to indicate the economy of the transportation systems under consideration.

Under the given assumptions the results show a similar economy of operation for the three-stage chemical vehicle and the two-stage chemical-nuclear vehicle. To make the comparison more comprehensive, the effect of increasing the reliability and the total development cost of the chemical-nuclear two-stage vehicle is studied.

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I. INTRODUCTION

A large amount of effort is being expended on long-range planning of program and vehicle requirements. This study attempts to supply some answers to long-range planning from the viewpoint of space flight economics. Specifically, this study attempts to compare the over-all economy of three-stage chemical vehicles and two-stage chemical-nuclear vehicles transporting large volumes of payload into a typical low altitude orbit. An attempt has been made to keep the assumptions as accurate as possible; however, a large number of assumptions are required and a rather complex procedure is needed to investigate this problem. Therefore, the assumptions regarding reliability and development cost, which seem to be those most subject to change, are presented as parameters. The procedure used to yield a comparison is given in the Appendix II. This procedure has been programmed on the LGP-30 computer, and the data shown here were obtained from this space flight economy procedure.

II. DISCUSSION

A. APPROACH

In comparing these two types of transport vehicles, take-off weight and desired annual transport volume are allowed to vary. Vehicles of each type are sized to represent a span of take-off weights yielding a span of payload capabilities. These transporters or orbital carriers are typical of their class and are based on the velocity requirements for a typical low altitude orbit. Operational assumptions, concerning mission reliability and pad time, establish firing rates and launch pad requirements for a given annual transport volume.

No consideration is given to the possibility that payload size and/or time interval of payload placement in orbit may be overriding factors. Also, no recovery or re-use of any stage of either vehicle is considered. These factors may develop into important considerations, but for simplicity and expediency they are not considered in the comparison.

B. ASSUMPTIONS

The assumptions can be divided logically into the categories of mission and vehicle, operational, and cost; but since the object is to compare a chemical-nuclear system and an all chemical system, these categories must be applied to each propulsive type. Therefore, the assumptions for the three-stage chemical vehicle will be discussed, and then the points which are peculiar to the two-stage chemical-nuclear vehicle will be given.

1. Three-stage Chemical Vehicle

a. Vehicle Assumptions

(1) The velocity capability of the vehicle was taken to be 9,300 m/sec, plus a flight performance reserve of 300 m/sec. This velocity corresponds approximately to a circular 96-minute orbit at an altitude of 307 nautical miles.

(2) Refer to Table 1 for specific impulse and propellant.

(3) Refer to Table II for a weight breakdown of the stages.

(4) No recovery of booster stages is included.

b. Operational Assumptions

(1) The transport volume requirement (weight of payloads per year transported into orbit) is used as an independent variable. Transport volumes of 1.0, 3.0, 10.0, and 20.0 million pounds per year are selected to cover the span of possible requirements on which a comparison may be based. These transport volumes can be converted into a given program or programs, depending on the need. All that is required for this study is to have a common basis from which the two propulsive types can be compared.

(2) An operational period of ten years is used in this investigation. The 10.0 million pound take-off weight vehicle has an initial operational date of 1970, while all other chemical vehicles enter into the first year of program operation in 1966.

(3) The vehicle size is the other main independent variable. The following take-off weights are used; 0.3, 1.0, 3.0, and 10.0 million pounds.

(4) These individual vehicles are assumed to be in a different development phase, thus having a different reliability when entering into the first year of operation. To determine the initial reliability for the first operational year, the number of vehicles of the respective take-off weights which have been flown must be assumed.

Take-off Weight - lbs	Accumulated Flights
300,000	200
1,000,000	25
3,000,000	9
10,000,000	1

(5) The mission reliability (successful delivery of payload into orbit) is shown in Figure 1. This is an empirical relationship which is considered typical for the vehicles under consideration. Only reliability curve Number 1 is used for the three-stage chemical vehicles. Refer to Tables IV-IX and Figures 4, 5, and 9.

c. Cost Assumptions

(1) Figure 2 shows the variation in production cost as a function of production number for the period 1964 through 1975. This plot is valid for a unit dry weight of 100,000 pounds. A weight correction factor for other unit dry weights can be obtained from Figure 3. This unit dry weight corresponds to the hardware weight, W_s, shown in Table II.

(2) Figure 3 shows an estimate of the variation of the development cost with stage dry weight.

(3) The vehicles are assumed to be transported over a distance of 1,000 miles at a cost of $1/lb.

(4) The propellant cost per pound of mixture is assumed to be $0.03/lb for LOX/RP and $0.20/lb for LOX/LH_2.

(5) Other cost assumptions are vehicle launch cost, range cost, and facility and GSE cost. These costs are functions of pad time per launch, annual firing rate, and take-off weight. The relationships used in estimating these costs are given in Appendix II.

2. Two-stage Chemical-Nuclear Vehicle

a. Vehicle Assumptions

(1) Refer to Table I for specific impulse and propellant.

(2) Refer to Table III for a weight breakdown of the stages.

(3) Other assumptions are identical to those made for the three-stage chemical vehicle.

b. Operational Assumptions

(1) The vehicle sizes and initial operational dates are as follows:

Take-off weight - lbs	Initial operational date
1,200,000	1968
2,400,000	1970
10,000,000	1972

(2) The number of accumulated flights at the initial operational date is, in each case, assumed to be five.

(3) Each of the mission reliability curves shown on Figure 1 is used for the two-stage chemical-nuclear vehicle. The variation of this assumption illustrates its effect on total operating cost and makes allowance for the possibility of superior reliability for the two-stage vehicle. Refer to Figures 5, 6, 7, and 9 through 17.

(4) Other assumptions are identical to those made for the three-stage chemical vehicle.

c. Cost Assumptions

(1) For the nuclear stage, Figure 2 is used only to obtain the production cost of the fuselage, (W_3), and the shielding. The production cost of the propulsion system, (W_4), is assumed to be \$200/lb. This assumption for the propulsion system is held constant for each vehicle size class with no cost decrease for production learning assumed. The cost of the reactor fuel is considered separately as \$8000/lb.

(2) The development cost for the nuclear stage is assumed to be as follows:

Take-off weight (million lbs)	1.2	2.4	10
Engine cost (million \$)	150	250	400
Reactor cost (million \$)	150	160	250
R&D GSE cost (million \$)	150	175	200
Total (million \$)	450	585	850

(3) The propellant cost is assumed to be \$0.20/lb.

(4) Other assumptions are identical to those made for the three-stage chemical vehicle.

C. OPERATIONAL DATA

Under the stated assumptions, certain operational features result. The annual transport volume and mission reliability establish an annual firing rate, and the annual firing rate establishes a pad time requirement from which the number of pads required can be determined. These two major operational features, annual firing rate and launch pad requirements, are shown in Tables IV and V and Figure 4. Tables IV and V show the launch rates for each consecutive year of operation as a function of take-off weight and annual transport volume. Figure 4 shows the launch pad requirement for the first and last operational years as a function of take-off weight and annual transport volume. The decrease in firing rate for each consecutive year of operation is due to increased mission reliability; the decrease in pad requirement between the first and last operational years is due to the decreasing pad time per launch.

The pad requirement for the last operational year is approximately one-tenth of that for the first year's operation. This means that throughout the course of the operational period several pads are not being used. The cost of this inefficiency in pad utilization is a relatively small portion of the total operating cost; however, an actual program would probably be carried out by building up to a fairly constant number of pads and making maximum use of them. Such an approach would result in a steady increase in the annual transport volume instead of a constant yearly value.

III. RESULTS

A distribution of the total operating cost for each propulsive type and for each annual transport volume is given in Tables VI through XIII. The data for this cost distribution is based on reliability curve Number 1 of Figure 1 and is included so that individual comparisons between cost items for each propulsive type may be made. From these tables it can be seen that the indirect operating cost, comprised of GSE and facilities, range cost, and vehicle development, is lower for the two-stage chemical-nuclear vehicle. Although individual items of GSE and facility for the chemical-nuclear vehicle cost more, the total cost of these items for a given program is less, because the pad requirement is less than that for the three-stage chemical vehicle. The range cost is less for the chemical-nuclear vehicle because the annual firing rate is lower than that required for the three-stage chemical vehicle. The vehicle development costs are comparable for each propulsive type.

Figures 5, 6, and 7 compare the direct operating cost of each propulsive type using the three reliability curves shown in Figure 1 for the two-stage chemical-nuclear vehicles only. The direct operating cost of the chemical-nuclear vehicles is much less than that for the three-stage chemical vehicles at the lower transport volumes. At the higher transport volumes (10×10^6 lb/yr and 20×10^6 lb/yr) there is little difference in direct operating cost except for the higher take-off weights. The decrease in direct operating cost of the chemical-nuclear vehicle due to increase in reliability can also be obtained from these figures.

The percentage increase in total operating cost of the chemical-nuclear vehicles due to increasing the basic development cost by factors of two and three is shown in Figure 8. These data are based on reliability curve Number 1 of Figure 1. For the larger transport volumes the effect of doubling and tripling the basic development cost is relatively small.

Figures 9 through 17 summarize the results of the study by presenting the total operating cost in $/lb of payload in orbit for the selected annual transport volumes as a function of take-off weight. For the chemical-nuclear vehicle these figures show the effect of increasing development cost and reliability.

IV. CONCLUSIONS

Based on the stated assumptions and calculation procedure, the following conclusions are made:

1. There is little difference in total operating cost of the two propulsive types for the larger annual transport volumes ($10 \cdot 10^6$ lb/yr and $20 \cdot 10^6$ lb/yr). This is true even when the reliability and/or development cost of the chemical-nuclear vehicle is increased.

2. The smaller annual transport volumes ($1 \cdot 10^6$ lb/yr and $3 \cdot 10^6$ lb/yr) show a greater divergence in total operating cost for the two propulsive types. Increasing reliability tends to offset increasing development cost. It is difficult to weigh reliability against development cost, but under the assumptions used, development cost appears to have a more significant effect on total operating cost.

3. The two-stage chemical-nuclear vehicle requires an annual firing rate of approximately one-half that required for the three-stage chemical vehicle. This lower firing rate could be very important if pad times cannot be reduced in the manner assumed. The decrease in pad requirements, and therefore, real estate, could also be very important.

4. The results indicate that operational requirements (payload size, rendezvous, firing rate, real estate, etc.), rather than economy, will determine the most desirable vehicle type and size.

5. Based on the assumptions used in this study, it appears that the minimum specific transportation cost of payloads, into low altitude orbits, is about $150/lb.

PROPULSION DATA FOR TYPICAL 3-STAGE CHEMICAL
AND 2-STAGE CHEMICAL - NUCLEAR VEHICLES

TABLE I

PROPULSION TYPE	TAKE-OFF WEIGHT	STAGE	I_{SP}	PROPELLANT
3 Stage Chemical	300,000	I	290 mean	LOX/RP
		II	425 vacuum	LOX/LH_2
		III	425 vacuum	LOX/LH_2
	1,000,000	I	290 mean	LOX/RP
		II	425 vacuum	LOX/LH_2
		III	425 vacuum	LOX/LH_2
	3,000,000	I	290 mean	LOX/RP
		II	425 vacuum	LOX/LH_2
		III	425 vacuum	LOX/LH_2
	10,000,000	I	290 mean	LOX/RP
		II	425 vacuum	LOX/LH_2
		III	425 vacuum	LOX/LH_2
2 Stage Chem-Nucl	1,200,000	I	290 mean	LOX/RP
		II	900 vacuum	LH_2
	2,400,000	I	290 mean	LOX/RP
		II	900 vacuum	LH_2
	10,000,000	I	290 mean	LOX/RP
		II	900 vacuum	LH_2

WEIGHT DATA FOR TYPICAL 3-STAGE CHEMICAL VEHICLES

TABLE II

*Take-off Weight, W_o	300,000	1,000,000	3,000,000	10,000,000
STAGE I				
Cutoff Weight, W_c	148,600	495,400	1,486,000	4,954,000
Propellant Weight, $W_{6,7,8}$	156,454	520,686	1,555,674	5,162,130
Hardware Weight, W_s	20,300	64,000	174,500	467,000
STAGE II				
Stage Take-off Weight, W_o	123,240	415,400	1,268,900	4,370,000
Cutoff Weight, W_c	49,050	165,400	505,000	1,740,000
Propellant Weight, $W_{6,7,8}$	76,276	256,650	782,340	2,681,080
Hardware Weight, W_s	8,340	26,510	73,700	204,200
STAGE III				
Stage Take-off Weight, W_o	38,620	132,150	413,800	1,485,600
Cutoff Weight, W_c	15,380	52,590	164,800	591,000
Propellant Weight, $W_{6,7,8}$	23,893	81,674	255,016	911,940
Hardware Weight, W_s	2,612	8,460	24,060	69,350
PAYLOAD				
Gross Dry Payload, $W_1 + W_2$	12,125	42,020	134,720	504,300
Guidance, Control, and Instrument Package, W_2	1,745	2,200	2,930	4,300
Total Payload, W_1	10,380	39,820	131,780	500,000
Growth Factor, M	28.9	25.1	22.8	20.0

*All weights are in pounds.

WEIGHT DATA FOR TYPICAL 2-STAGE CHEMICAL - NUCLEAR VEHICLES

TABLE III

*Take-off Weight, W_o	1,200,000	2,400,000	10,000,000
STAGE I Cutoff Weight, W_c	600,000	1,150,000	5,000,000
Propellant Weight, $W_{6,7,8}$	620,000	1,277,070	5,075,000
Hardware Weight, W_s	80,000	96,730	425,000
STAGE II Stage Take-off Weight, W_o	500,000	1,036,200	4,500,000
Cutoff Weight, W_c	197,000	371,130	1,770,000
Propellant Weight, $W_{6,7,8}$	308,000	679,200	2,755,000
Fuselage Weight, W_3	35,000	70,000	275,000
Propulsion Weight, W_4	20,000	40,000	100,000
Shielding Weight	2,000	2,000	3,000
PAYLOAD Gross Dry Payload, $W_1 + W_2$	133,500	250,630	1,374,000
Guidance, Control and Instrument Package, W_2	3,500	3,500	4,000
Total Payload, W_1	130,000	247,130	1,370,000
Growth Factor, M	9.23	9.72	7.30

*All weights are in pounds.

TABLE IV NUMBER OF FIRINGS PER YEAR FOR 3-STAGE CHEMICAL VEHICLES

TRANSPORT VOLUME	TAKE-OFF WEIGHT	*NUMBER OF FIRINGS PER YEAR (CONSECUTIVE YEAR OF OPERATION)									
Lb/Yr	Lb	1	2	3	4	5	6	7	8	9	10
$1 \cdot 10^6$	300,000	119	114	110	108	106	104	103	101	101	101
	1,000,000	40	37	35	33	33	32	31	31	30	30
	3,000,000	15	13	12	12	12	11	11	11	11	10
	10,000,000	5	5	4	4	4	4	3	3	3	3
$3 \cdot 10^6$	300,000	342	317	305	305	304	304	304	304	304	304
	1,000,000	110	98	93	89	87	85	84	83	81	80
	3,000,000	40	34	32	31	30	29'	29	29	28	28
	10,000,000	13	11	10	10	9	9	9	9	9	8
$10 \cdot 10^6$	300,000	1052	1015	1014	1014	1014	1014	1014	1014	1014	1014
	1,000,000	325	287	272	265	265	265	264	264	264	264
	3,000,000	115	99	94	90	88	86	84	83	82	81
	10,000,000	36	31	29	28	27	26	26	25	25	25
$20 \cdot 10^6$	1,000,000	604	535	529	529	529	529	529	529	528	528
	3,000,000	211	184	174	167	163	160	157	155	153	152
	10,000,000	66	57	53	51	50	48	48	47	46	46

* Reliability Curve Number 1.

TABLE V

NUMBER OF FIRINGS PER YEAR FOR 2-STAGE CHEMICAL - NUCLEAR VEHICLES

TRANSPORT VOLUME	TAKE-OFF WEIGHT	*NUMBER OF FIRINGS PER YEAR (CONSECUTIVE YEAR OF OPERATION)									
Lb/Yr	Lb	1	2	3	4	5	6	7	8	9	10
$1 \cdot 10^6$	1,200,000	16	13	13	12	12	11	11	11	11	11
	2,400,000	9	8	7	7	7	7	6	6	6	6
	10,000,000	2	2	2	2	2	2	1	1	1	1
$3 \cdot 10^6$	1,200,000	41	35	33	32	30	30	29	29	28	28
	2,400,000	24	20	19	18	17	17	17	16	16	16
	10,000,000	5	5	4	4	4	4	4	4	4	3
$10 \cdot 10^6$	1,200,000	117	101	95	91	89	87	85	84	83	82
	2,400,000	67	57	54	52	50	49	48	47	47	46
	10,000,000	15	13	12	12	11	11	11	10	10	10
$20 \cdot 10^6$	1,200,000	214	186	176	170	165	162	159	157	155	154
	2,400,000	123	105	99	96	93	91	89	88	87	86
	10,000,000	28	24	22	21	20	20	19	19	19	19

*Reliability Curve Number 1.

DISTRIBUTION OF TOTAL OPERATING COST ($ MILLION) FOR A 1,000,000 LB/YR TRANSPORT VOLUME

3-STAGE CHEMICAL VEHICLE

(RELIABILITY CURVE 1)

TABLE VI

	W_o(lb) 300,000	W_o(lb) 1,000,000	W_o(lb) 3,000,000	W_o(lb) 10,000,000
Vehicle Production	2894	3539	4034	5746
Propellant	26	28	30	32
Vehicle Transportation	35	34	32	28
Vehicle Launch Operations	723	570	491	549
DIRECT OPERATING COST	3678	4171	4587	6355
AVERAGE SPECIFIC DIRECT OPERATING COST ($/1b)	368	417	459	636
Range Cost	237	90	47	31
Ground Support Equipment and Facility	712	480	382	333
Vehicle Development	354	794	1613	3414
INDIRECT OPERATING COST	1303	1364	2042	3778
AVERAGE SPECIFIC INDIRECT OPERATING COST ($/1b)	130	136	204	378
TOTAL OPERATING COST	4981	5535	6629	10133
AVERAGE TOTAL SPECIFIC OPERATING COST ($/1b)	498	553	663	1013

DISTRIBUTION OF TOTAL OPERATING COST ($ MILLION) FOR A 3,000,000 LB/YR TRANSPORT VOLUME

3-STAGE CHEMICAL VEHICLE

(RELIABILITY CURVE 1)

TABLE VII

	W_o(lb) 300,000	W_o(lb) 1,000,000	W_o(lb) 3,000,000	W_o(lb) 10,000,000
Vehicle Production	5996	6614	7459	10453
Propellant	76	74	79	84
Vehicle Transportation	102	90	85	72
Vehicle Launch Operations	1875	1290	1049	952
DIRECT OPERATING COST	8049	8068	8672	11561
AVERAGE SPECIFIC DIRECT OPERATING COST ($/lb)	268	269	289	385
Range Cost	643	202	86	43
Ground Support Equipment and Facility	1950	1240	874	666
Vehicle Development	354	794	1613	3414
INDIRECT OPERATING COST	2947	2236	2573	4123
AVERAGE SPECIFIC INDIRECT OPERATING COST ($/lb)	98	75	86	137
TOTAL OPERATING COST	10996	10304	11245	15684
AVERAGE TOTAL SPECIFIC OPERATING COST ($/lb)	367	343	375	523

DISTRIBUTION OF TOTAL OPERATING COST ($ MILLION) FOR A 10,000,000 LB/YR TRANSPORT VOLUME

3-STAGE CHEMICAL VEHICLE

(RELIABILITY CURVE 1)

TABLE VIII

	W_o(lb) 300,000	W_o(lb) 1,000,000	W_o(lb) 3,000,000	W_o(lb) 10,000,000
Vehicle Production	12685	13046	14211	19234
Propellant	252	228	229	242
Vehicle Transportation	336	277	248	207
Vehicle Launch Operations	5857	3615	2723	2197
DIRECT OPERATING COST	19130	17166	17411	21880
AVERAGE SPECIFIC DIRECT OPERATING COST ($/lb)	191	172	174	219
Range Cost	2060	571	204	80
Ground Support Equipment and Facility	6005	3600	2514	1831
Vehicle Development	354	794	1613	3414
INDIRECT OPERATING COST	8419	4965	4331	5325
AVERAGE SPECIFIC INDIRECT OPERATING COST ($/lb)	84	50	43	53
TOTAL OPERATING COST	27549	22131	21742	27205
AVERAGE TOTAL SPECIFIC OPERATING COST ($/lb)	275	221	217	272

DISTRIBUTION OF TOTAL OPERATING COST ($ MILLION) FOR A 20,000,000 LB/YR TRANSPORT VOLUME

3-STAGE CHEMICAL VEHICLE

(RELIABILITY CURVE 1)

TABLE IX

	W_o (lb) 1,000,000	W_o (lb) 3,000,000	W_o (lb) 10,000,000
Vehicle Production	19417	20468	27000
Propellant	447	426	447
Vehicle Transportation	543	461	381
Vehicle Launch Operations	6795	4911	3845
DIRECT OPERATING COST	27202	26266	31673
AVERAGE SPECIFIC DIRECT OPERATING COST ($/lb)	136	131	158
Range Cost	1098	359	126
Ground Support Equipment and Facility	6640	4590	3330
Vehicle Development	774	1541	3414
INDIRECT OPERATING COST	8512	6490	6870
AVERAGE SPECIFIC INDIRECT OPERATING COST ($/lb)	43	32	34
TOTAL OPERATING COST	35714	32756	38543
AVERAGE TOTAL SPECIFIC OPERATING COST ($/lb)	179	164	193

DISTRIBUTION OF TOTAL OPERATING COST ($ MILLION) FOR A 1,000,000 LB/YR TRANSPORT VOLUME

2-STAGE CHEMICAL - NUCLEAR VEHICLE

(RELIABILITY CURVE 1)

TABLE X

	W_o(lb) 1,200,000	W_o(lb) 2,400,000	W_o(lb) 10,000,000
Vehicle Production	3048	3247	3747
Propellant	492	560	375
Vehicle Transportation	17	15	12
Vehicle Launch Operations	377	382	458
DIRECT OPERATING COST	3934	4204	4592
AVERAGE SPECIFIC DIRECT OPERATING COST ($/lb)	393	420	459
Range Cost	48	38	27
Ground Support Equipment and Facility	260	244	186
Vehicle Development	1018	1265	2741
INDIRECT OPERATING COST	1326	1547	2954
AVERAGE SPECIFIC INDIRECT OPERATING COST ($/lb)	133	155	295
TOTAL OPERATING COST	5260	5751	7546
AVERAGE TOTAL SPECIFIC OPERATING COST ($/lb)	526	575	755

DISTRIBUTION OF TOTAL OPERATING COST ($ MILLION) FOR A 3,000,000 LB/YR TRANSPORT VOLUME

2-STAGE CHEMICAL - NUCLEAR VEHICLE

(RELIABILITY CURVE 1)

TABLE XI

	W_o (lb) 1,200,000	W_o (lb) 2,400,000	W_o (lb) 10,000,000
Vehicle Production	5790	6178	7369
Propellant	1287	1464	990
Vehicle Transportation	44	38	33
Vehicle Launch Operations	817	714	624
DIRECT OPERATING COST	7938	8394	9016
AVERAGE SPECIFIC COST OPERATING COST ($/lb)	265	280	301
Range Cost	87	60	32
Ground Support Equipment and Facility	675	549	373
Vehicle Development	1018	1265	2741
INDIRECT OPERATING COST	1780	1874	3146
AVERAGE SPECIFIC INDIRECT OPERATING COST ($/lb)	59	62	105
TOTAL OPERATING COST	9718	10268	12162
AVERAGE TOTAL SPECIFIC OPERATING COST ($/lb)	324	342	405

DISTRIBUTION OF TOTAL OPERATING COST ($ MILLION) FOR A 10,000,000 LB/YR TRANSPORT VOLUME

2-STAGE CHEMICAL - NUCLEAR VEHICLE

TABLE XII

(RELIABILITY CURVE 1)

	W_o(lb) 1,200,000	W_o(lb) 2,400,000	W_o(lb) 10,000,000
Vehicle Production	11948	12671	14604
Propellant	3737	4224	2836
Vehicle Transportation	129	110	93
Vehicle Launch Operations	1928	1733	1249
DIRECT OPERATING COST	17741	18738	18782
AVERAGE SPECIFIC DIRECT OPERATING COST ($/lb)	177	187	188
Range Cost	207	127	47
Ground Support Equipment and Facility	1817	1525	932
Vehicle Development	1018	1265	2741
INDIRECT OPERATING COST	3042	2917	3720
AVERAGE SPECIFIC INDIRECT OPERATING COST ($/lb)	30	29	37
TOTAL OPERATING COST	20783	21655	22502
AVERAGE TOTAL SPECIFIC OPERATING COST ($/lb)	208	217	225

DISTRIBUTION OF TOTAL OPERATING COST ($ MILLION) FOR A 20,000,000 LB/YR TRANSPORT VOLUME

2-STAGE CHEMICAL - NUCLEAR VEHICLE

TABLE XIII (RELIABILITY CURVE 1)

	W_o (1b) 1,200,000	W_o (1b) 2,400,000	W_o (1b) 10,000,000
Vehicle Production	18499	17101	21474
Propellant	6943	7817	5201
Vehicle Transportation	239	204	171
Vehicle Launch Operations	3458	3085	1998
DIRECT OPERATING COST	29139	28207	28844
AVERAGE SPECIFIC DIRECT OPERATING COST ($/1b)	146	141	144
Range Cost	364	215	66
Ground Support Equipment and Facility	3270	2805	1585
Vehicle Development	1018	1265	2741
INDIRECT OPERATING COST	4652	4285	4392
AVERAGE SPECIFIC INDIRECT OPERATING COST ($/1b)	23	21	22
TOTAL OPERATING COST	33791	32492	33236
AVERAGE TOTAL SPECIFIC OPERATING COST ($/1b)	169	162	166

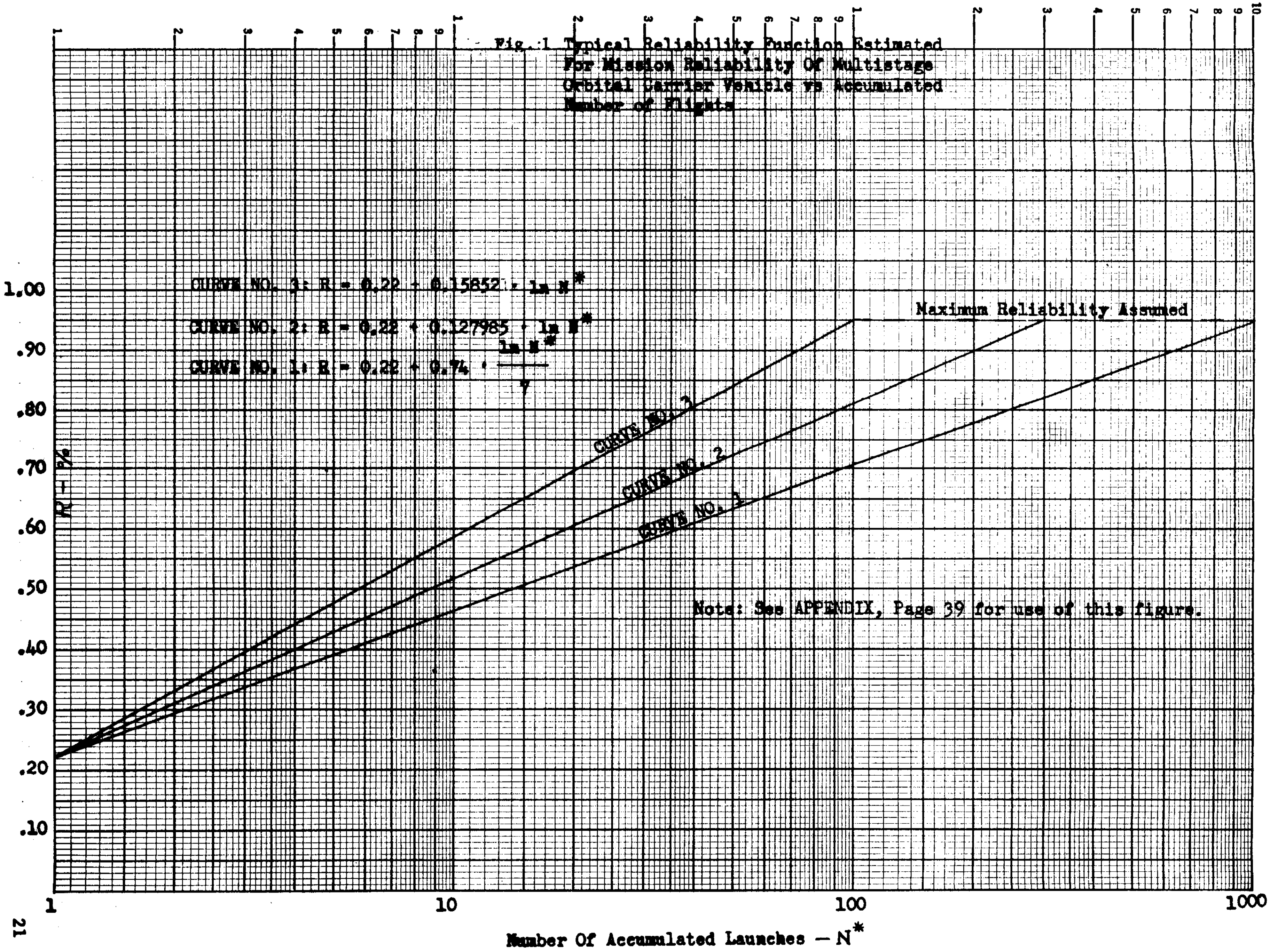


Fig. 1 Typical Reliability Function Estimated For Mission Reliability Of Multistage Orbital Carrier Vehicle vs Accumulated Number of Flights

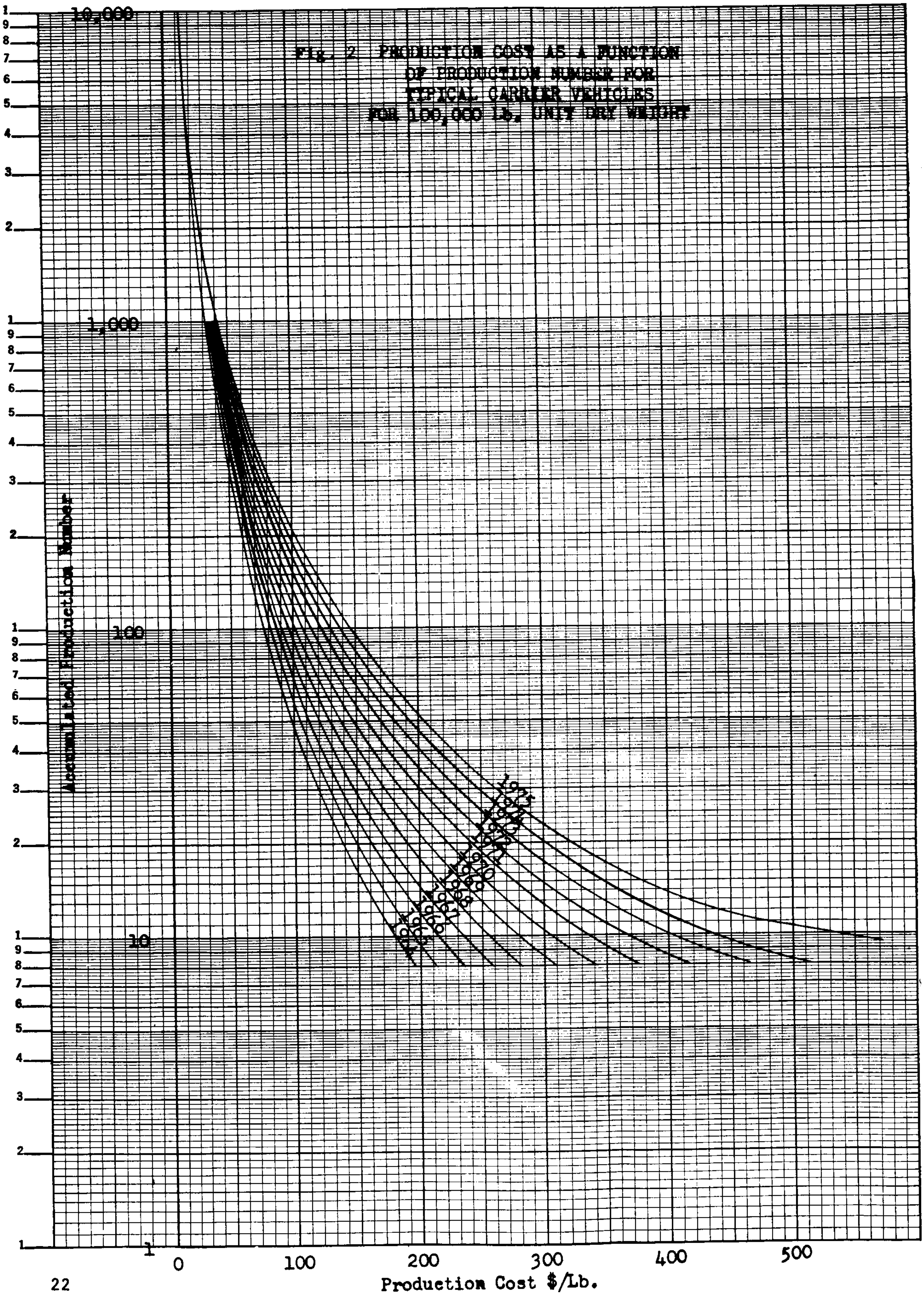


Fig. 2 PRODUCTION COST AS A FUNCTION OF PRODUCTION NUMBER FOR TYPICAL CARRIER VEHICLES FOR 100,000 Lb. UNIT DRY WEIGHT

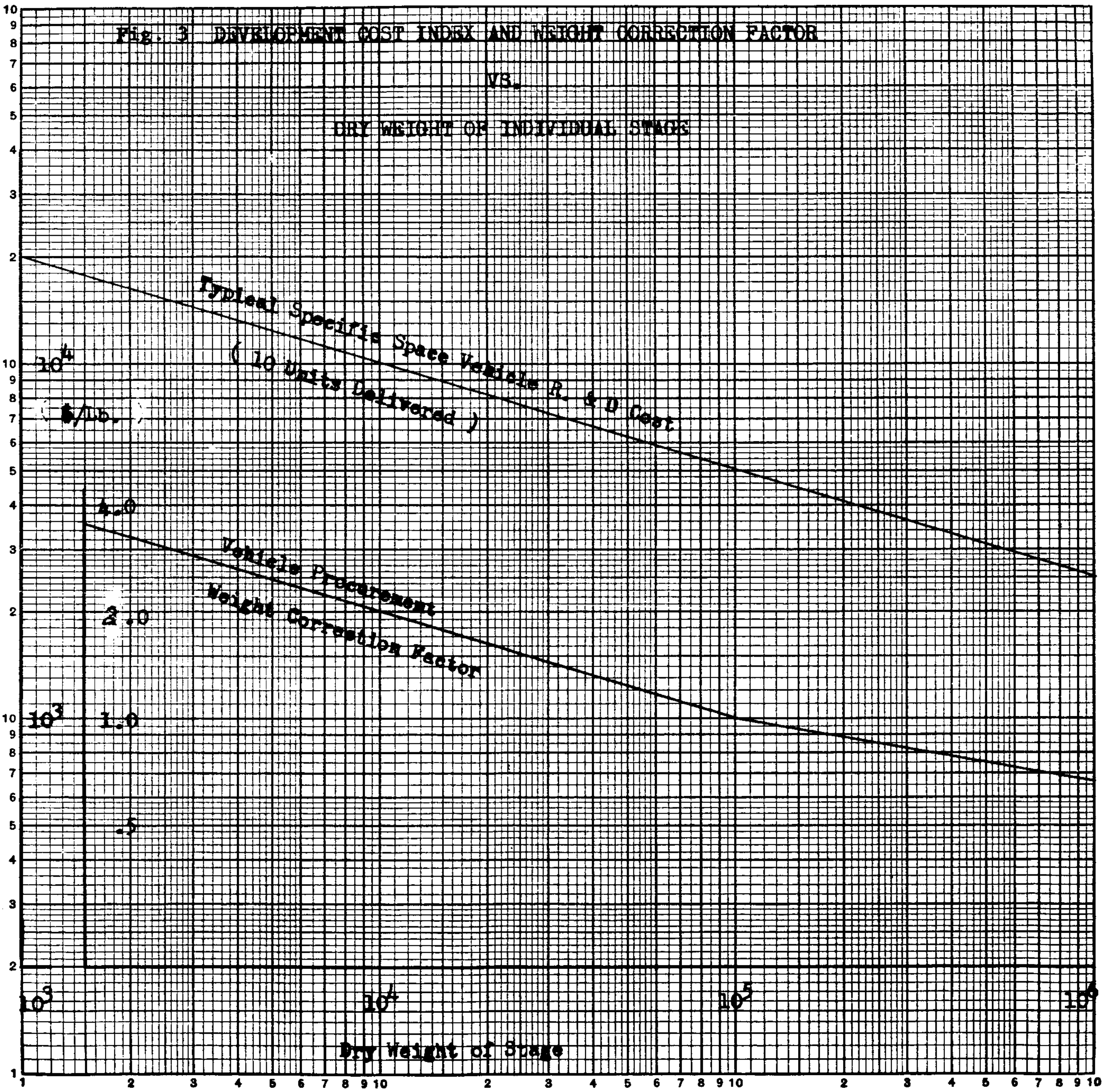
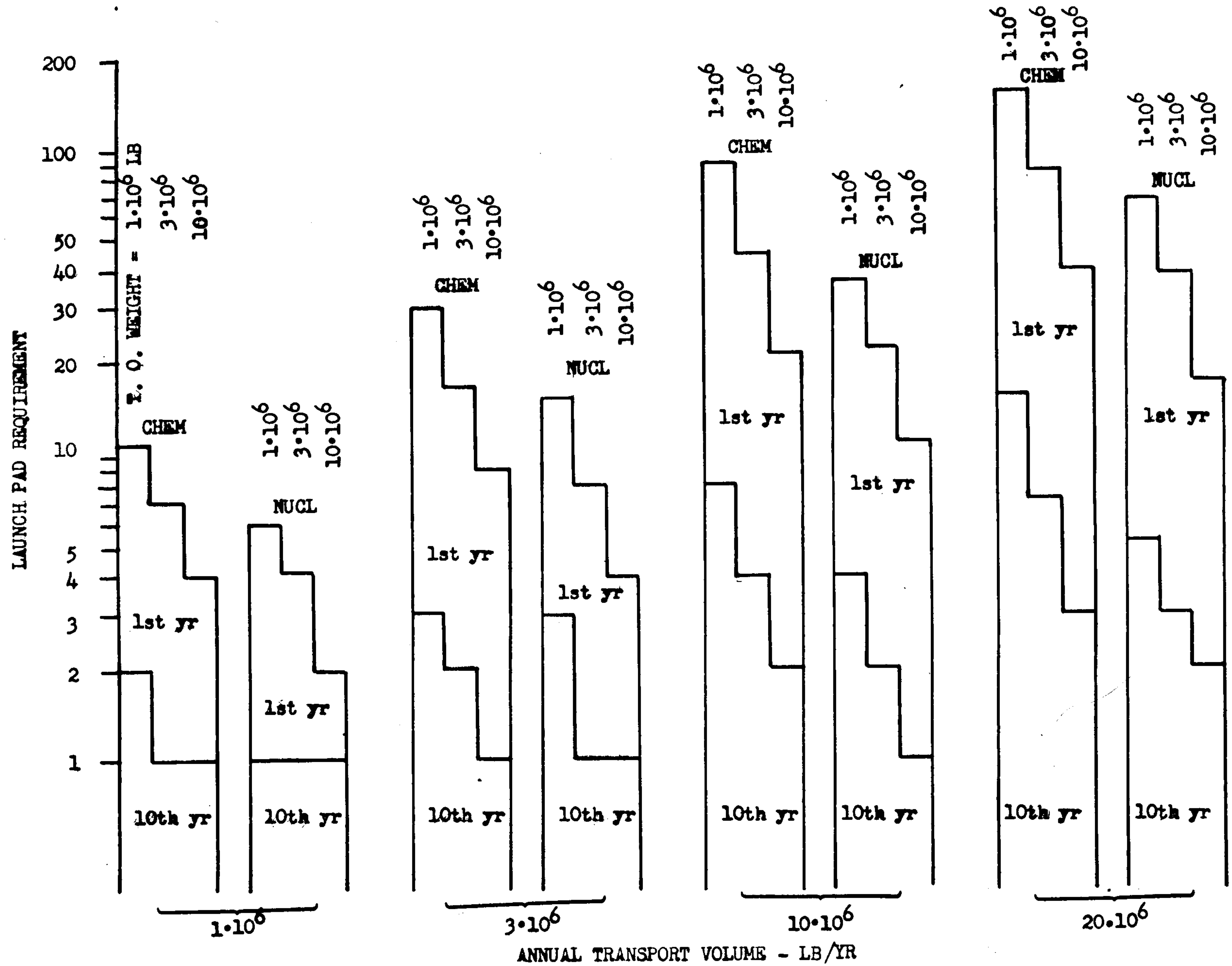


Fig. 3 DEVELOPMENT COST INDEX AND WEIGHT CORRECTION FACTOR

VS.

DRY WEIGHT OF INDIVIDUAL STAGE

Fig. 4 LAUNCH PAD REQUIREMENTS FOR 3-STAGE CHEMICAL AND 2-STAGE CHEMICAL-NUCLEAR VEHICLES AT VARIOUS TAKE-OFF WEIGHTS AND CONSTANT ANNUAL TRANSPORT VOLUMES FOR 1ST & 10TH YR (RELIABILITY CURVE NUMBER 1)



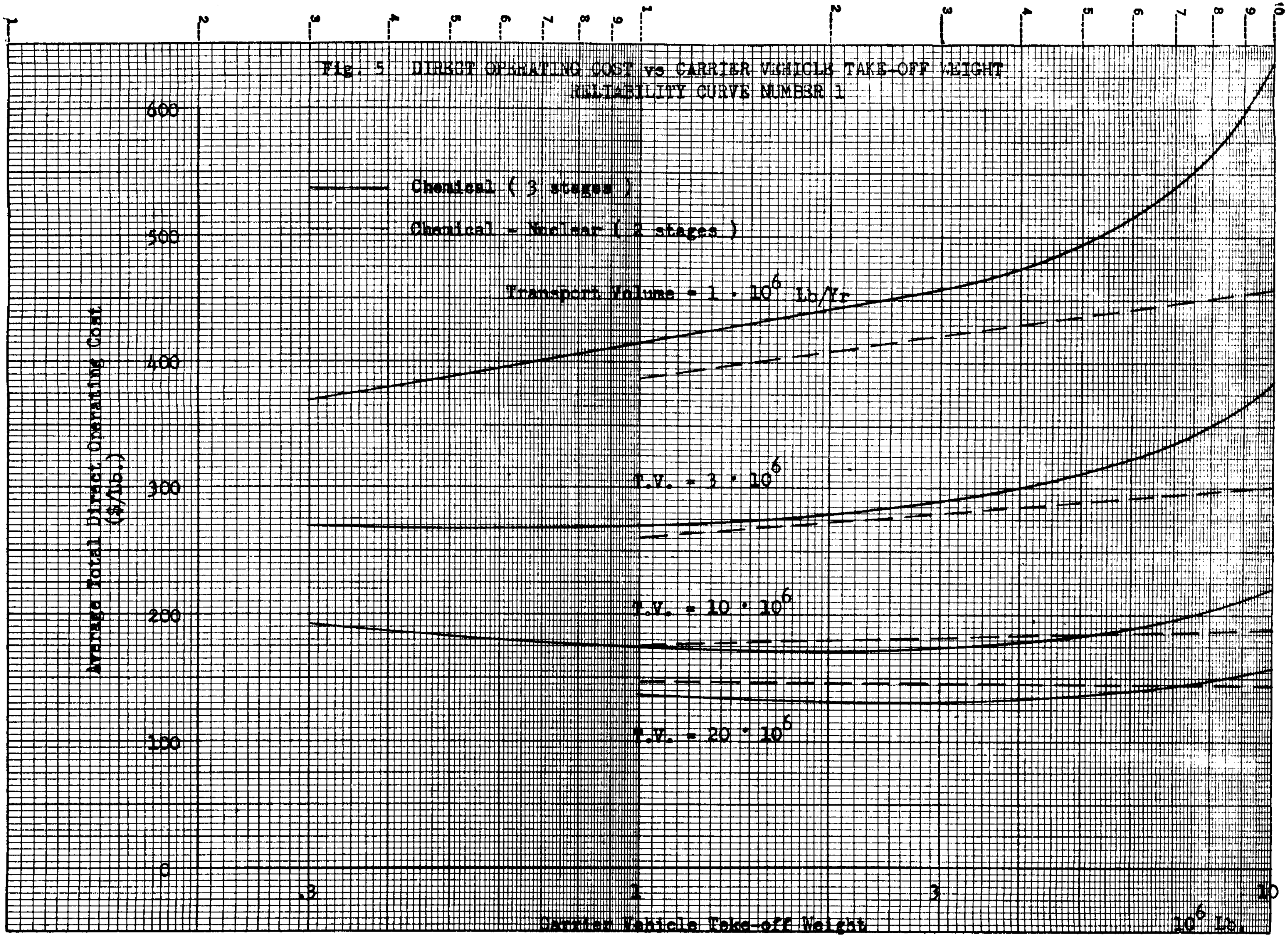


Fig. 5 DIRECT OPERATING COST vs CARRIER VEHICLE TAKE-OFF WEIGHT
RELIABILITY CURVE NUMBER 1

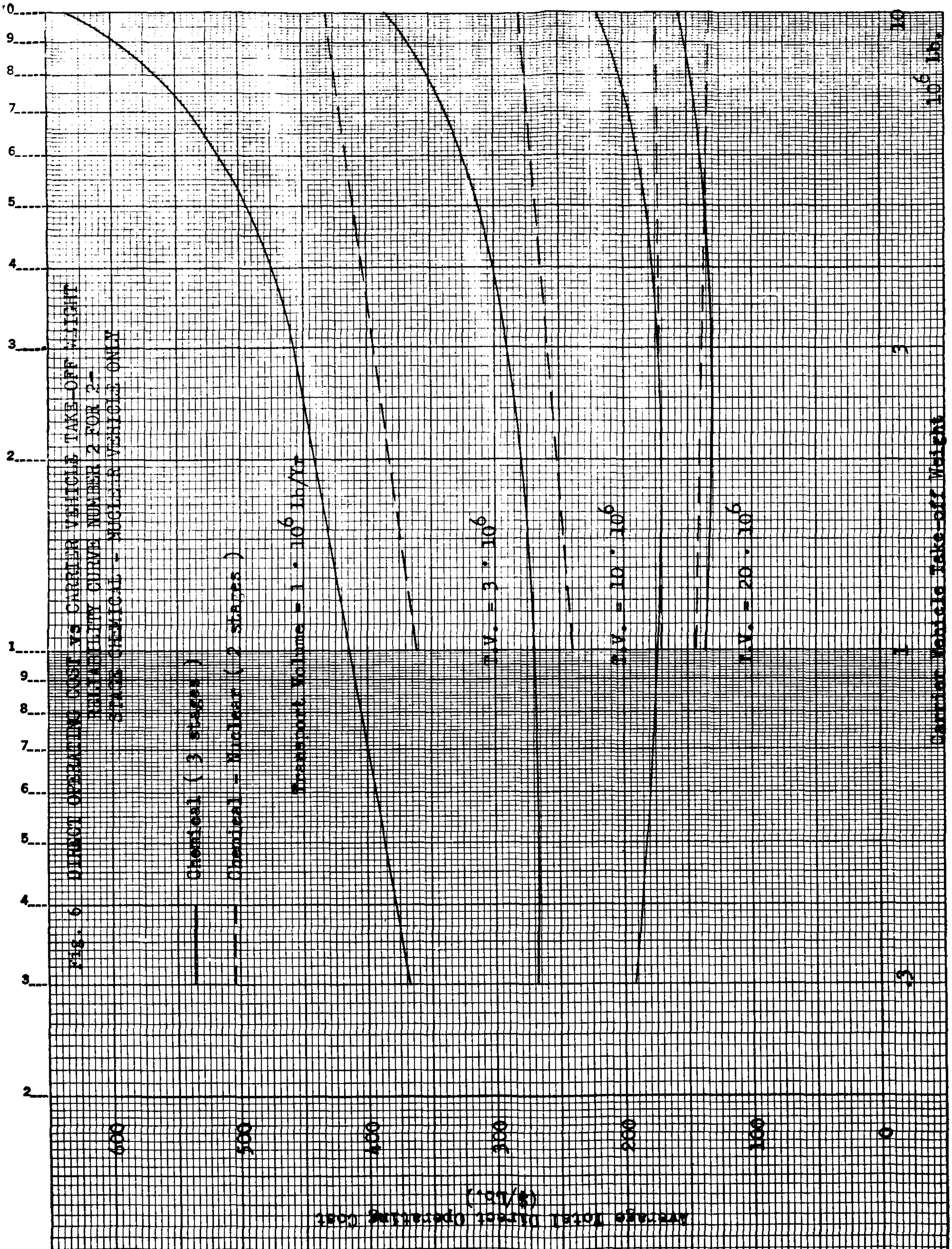


Fig. 6 DIRECT OPERATING COST VS CARRIER VEHICLE TAKE-OFF WEIGHT
RELIABILITY CURVE NUMBER 2 FOR 2-
STAGE CHEMICAL - NUCLEAR VEHICLE ONLY

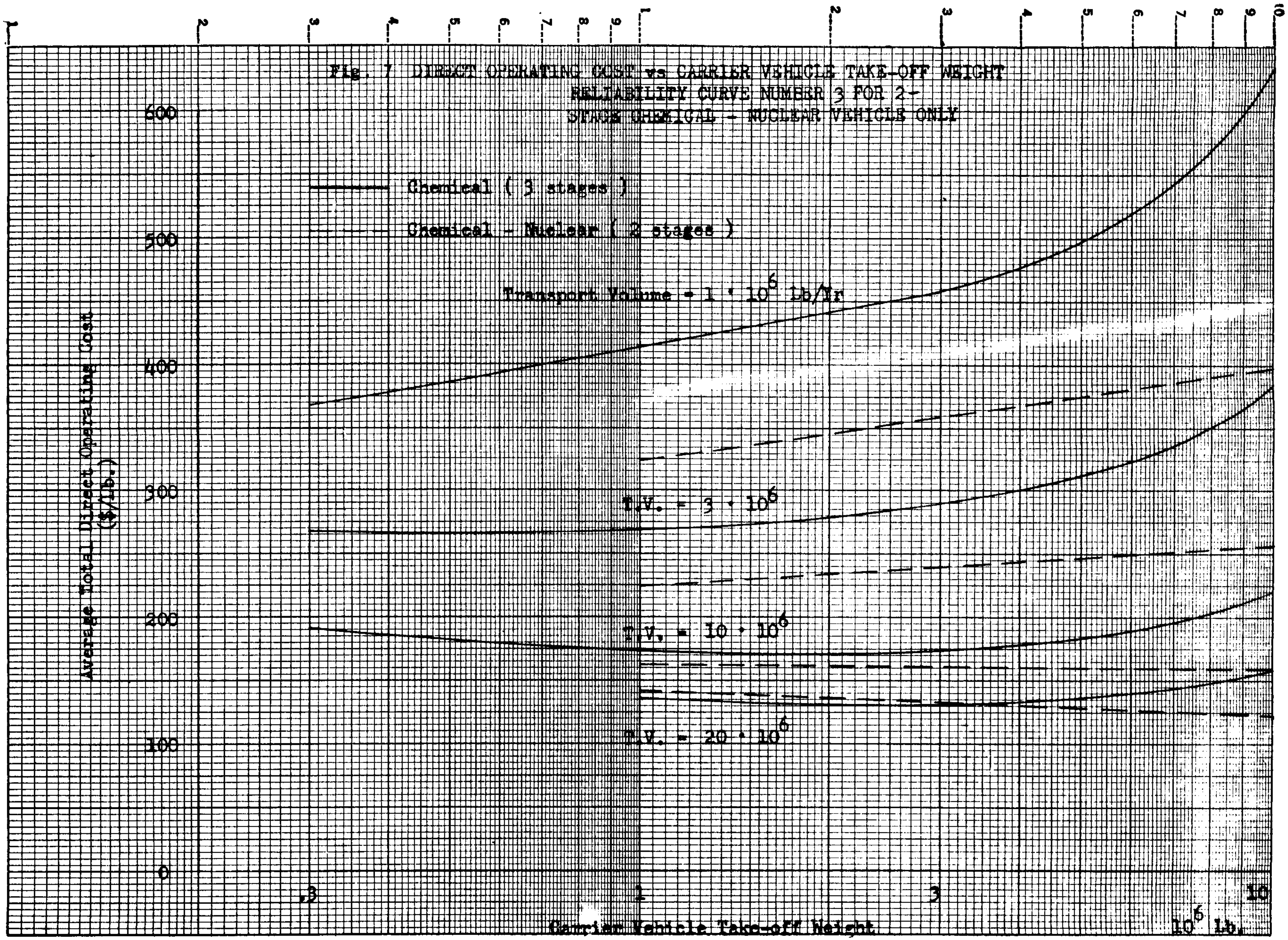


Fig. 7 DIRECT OPERATING COST vs CARRIER VEHICLE TAKE-OFF WEIGHT RELIABILITY CURVE NUMBER 3 FOR 2-STAGE CHEMICAL - NUCLEAR VEHICLE ONLY

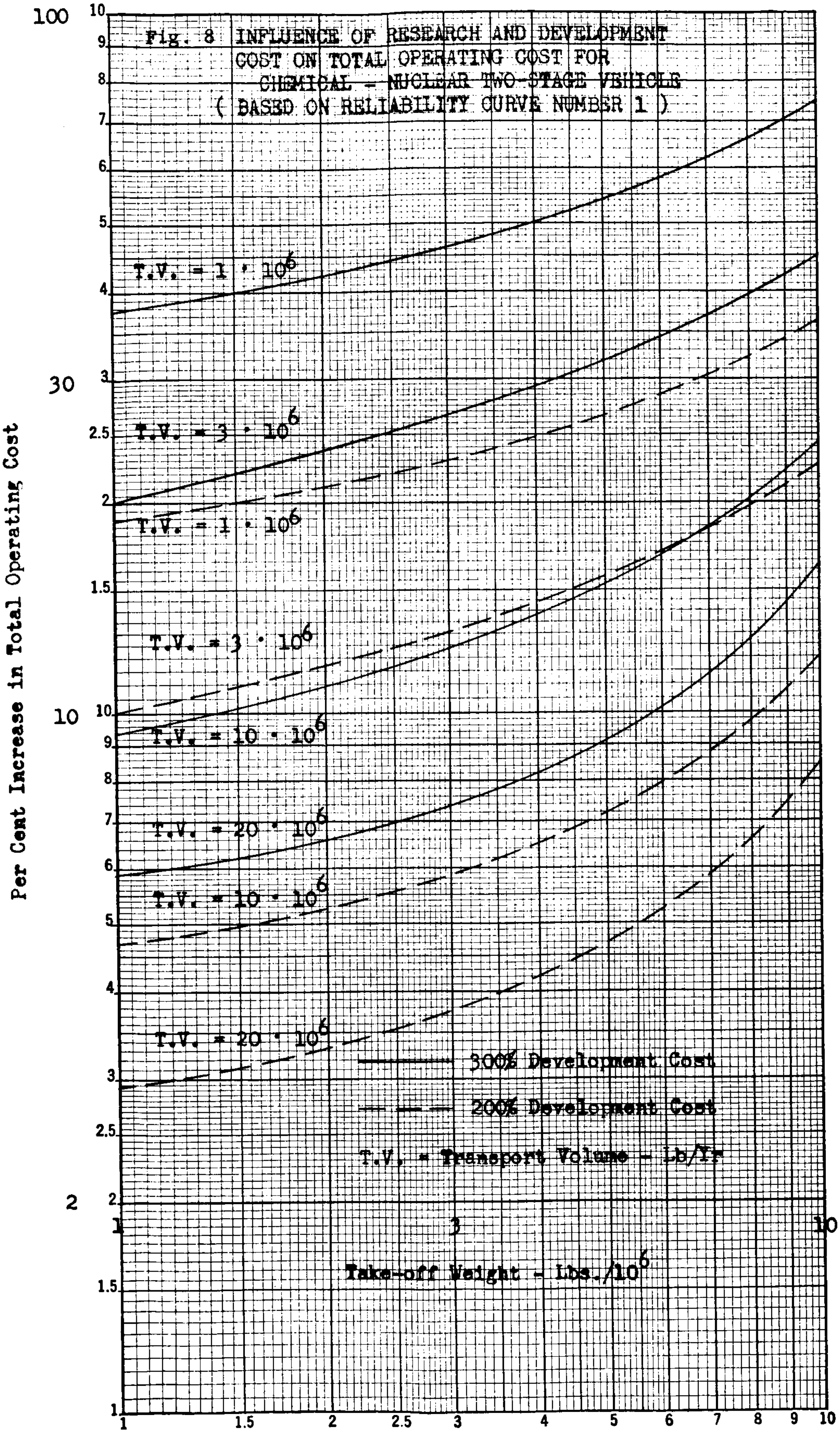


Fig. 8 INFLUENCE OF RESEARCH AND DEVELOPMENT COST ON TOTAL OPERATING COST FOR CHEMICAL - NUCLEAR TWO-STAGE VEHICLE (BASED ON RELIABILITY CURVE NUMBER 1)
T.V. = 1 · 10^6
T.V. = 3 · 10^6
T.V. = 1 · 10^6
T.V. = 3 · 10^6
T.V. = 10 · 10^6
T.V. = 20 · 10^6
T.V. = 10 · 10^6
T.V. = 20 · 10^6
300% Development Cost
200% Development Cost
T.V. = Transport Volume - Lb/Yr
Per Cent Increase in Total Operating Cost
Take-off Weight - Lbs./10^6
100
30
10
2
1
3
10

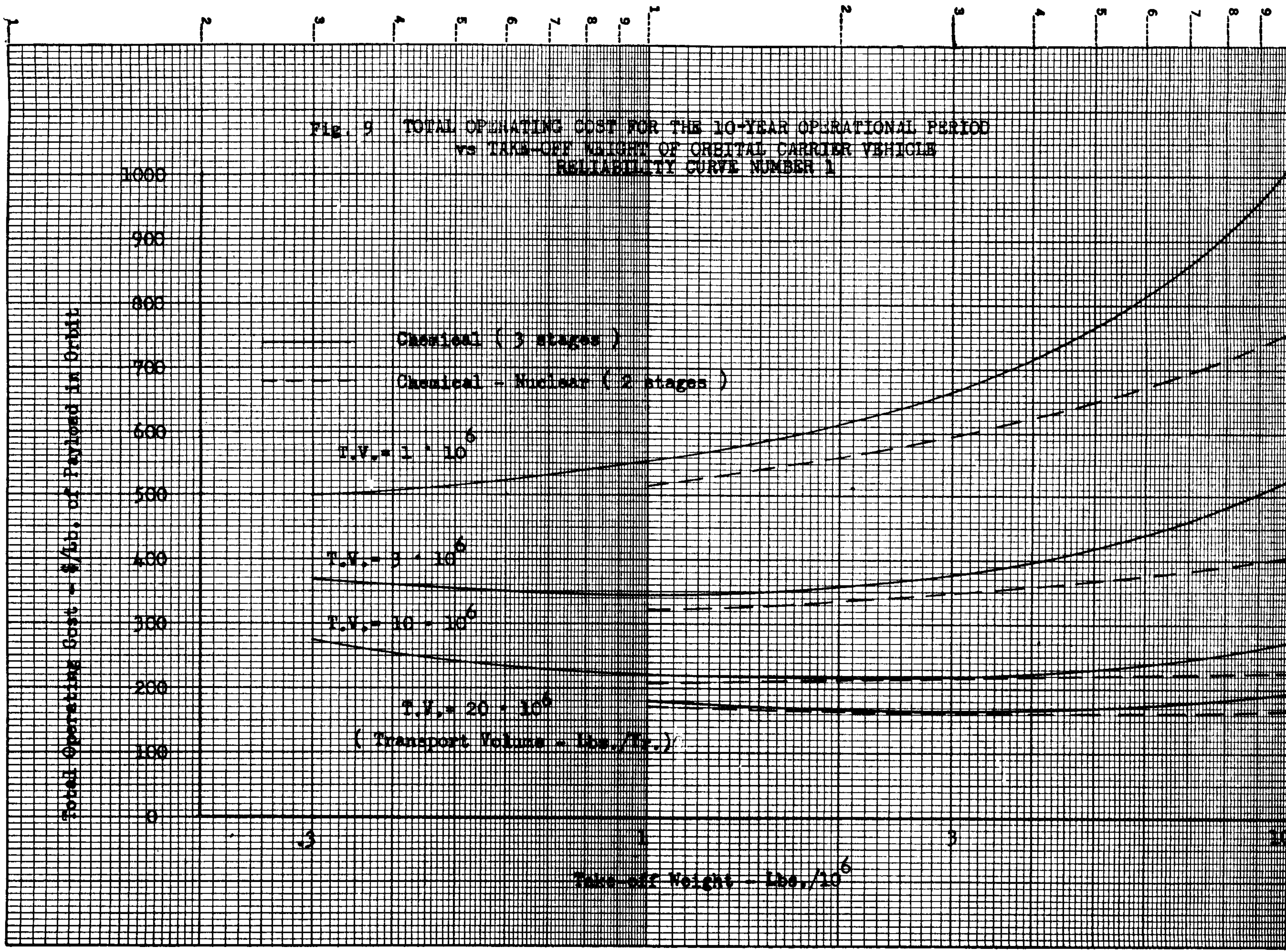


Fig. 9 TOTAL OPERATING COST FOR THE 10-YEAR OPERATIONAL PERIOD vs TAKE-OFF WEIGHT OF ORBITAL CARRIER VEHICLE RELIABILITY CURVE NUMBER 1

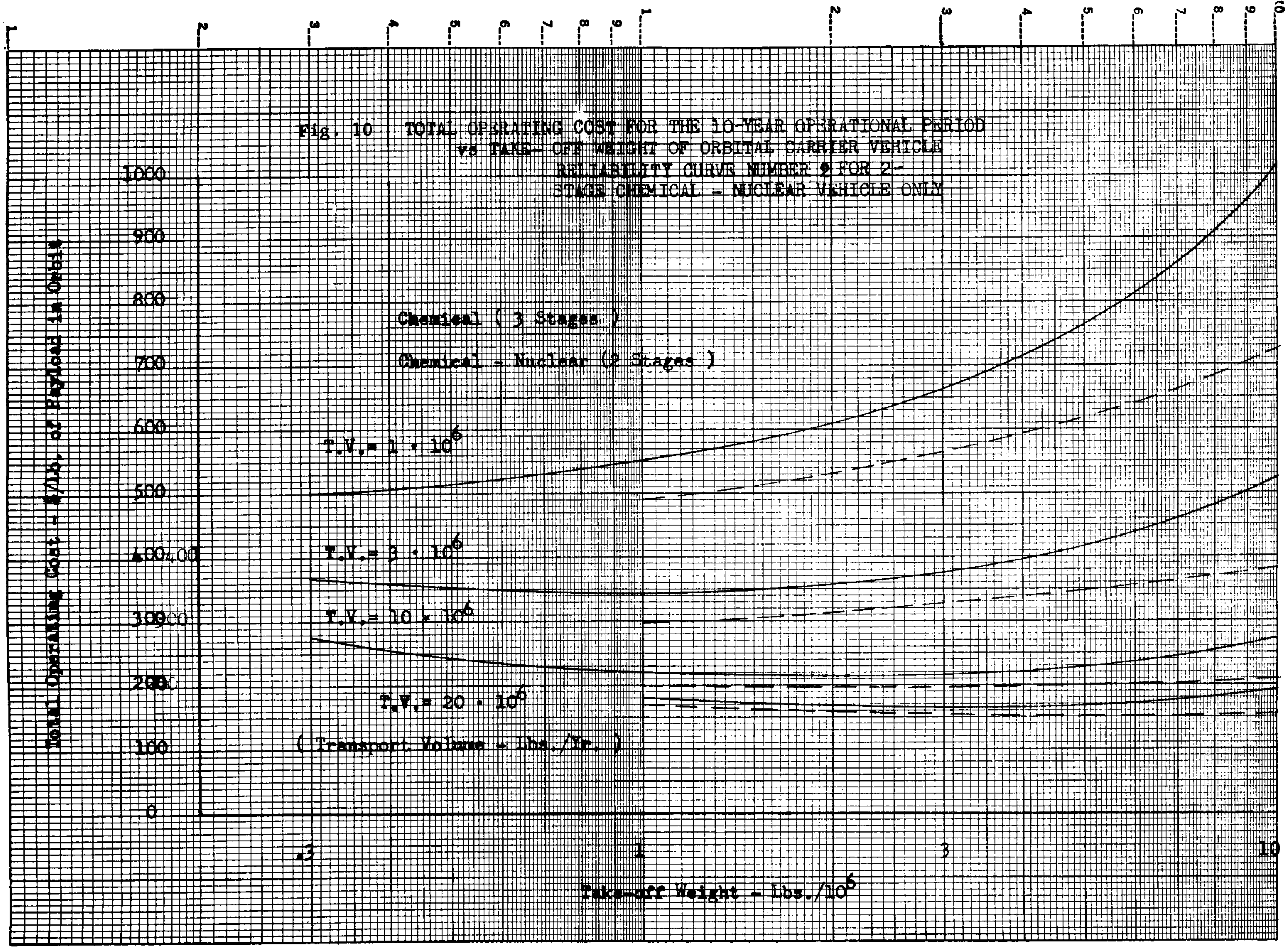


Fig. 10 TOTAL OPERATING COST FOR THE 10-YEAR OPERATIONAL PERIOD vs TAKE- OFF WEIGHT OF ORBITAL CARRIER VEHICLE RELIABILITY CURVE NUMBER 2 FOR 2-STAGE CHEMICAL - NUCLEAR VEHICLE ONLY

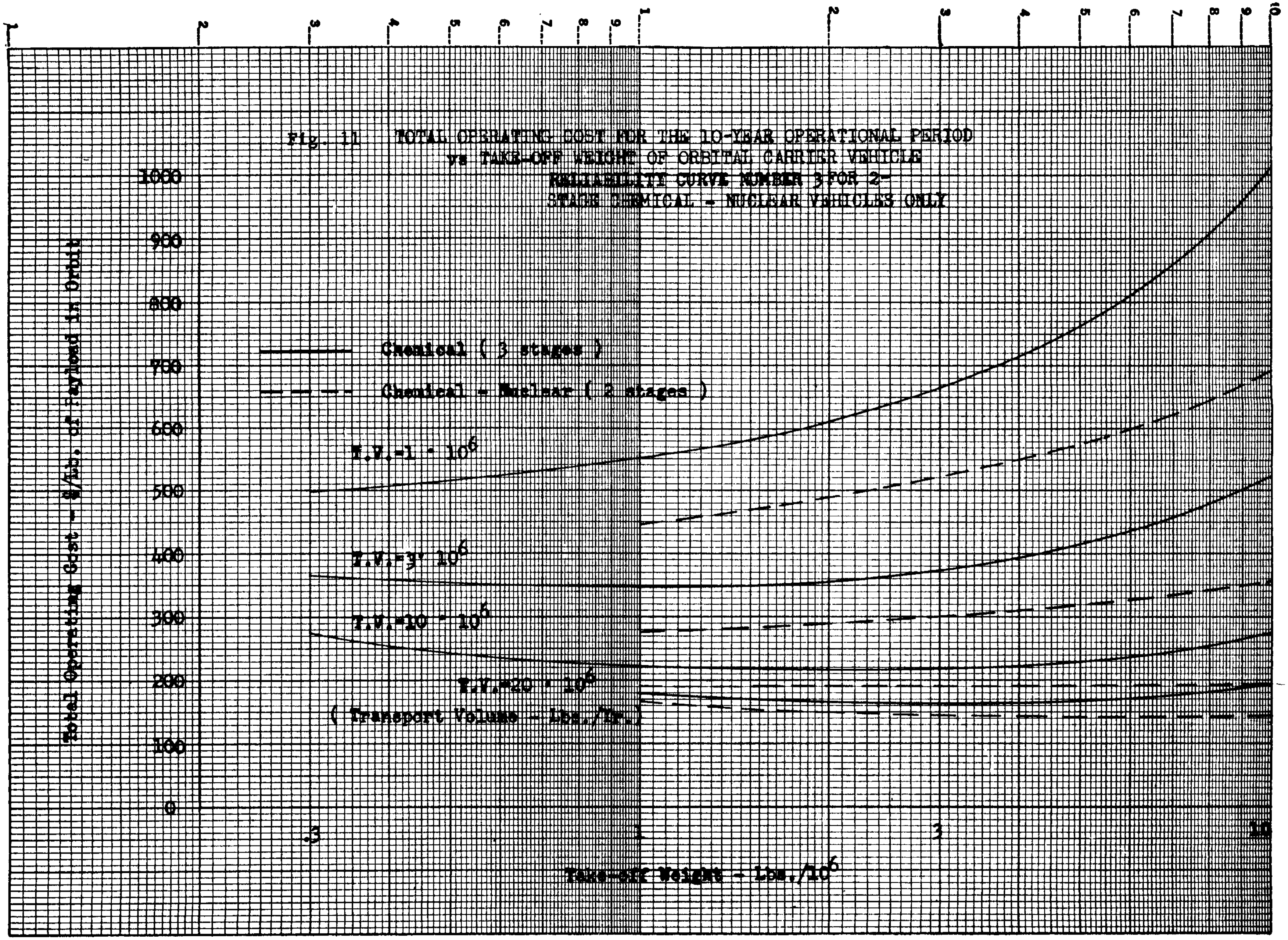


Fig. 11 TOTAL OPERATING COST FOR THE 10-YEAR OPERATIONAL PERIOD vs TAKE-OFF WEIGHT OF ORBITAL CARRIER VEHICLE
RELIABILITY CURVE NUMBER 3 FOR 2-STAGE CHEMICAL - NUCLEAR VEHICLES ONLY

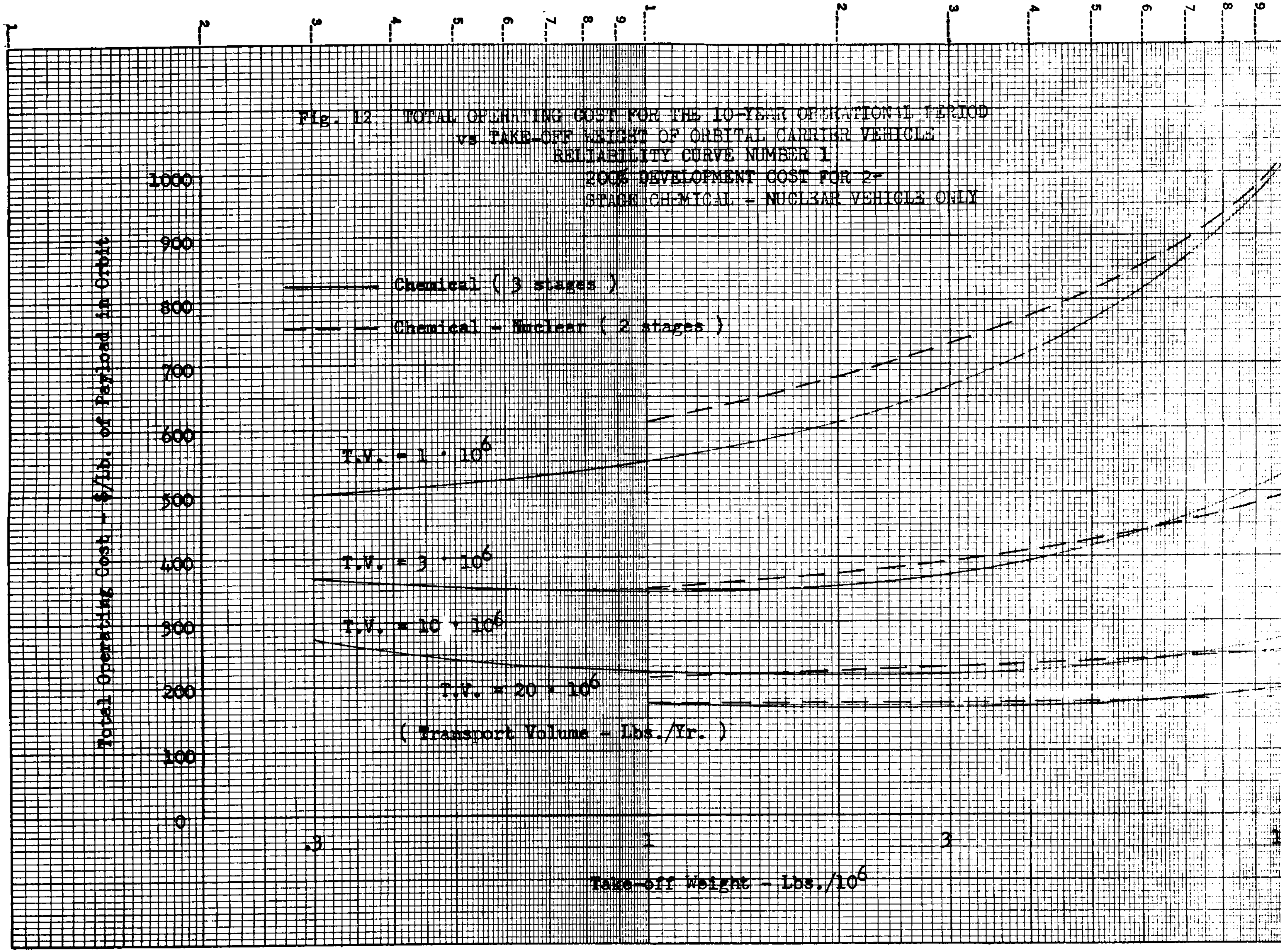


Fig. 12 TOTAL OPERATING COST FOR THE 10-YEAR OPERATIONAL PERIOD vs TAKE-OFF WEIGHT OF ORBITAL CARRIER VEHICLE
RELIABILITY CURVE NUMBER 1
200% DEVELOPMENT COST FOR 2-STAGE CHEMICAL - NUCLEAR VEHICLE ONLY

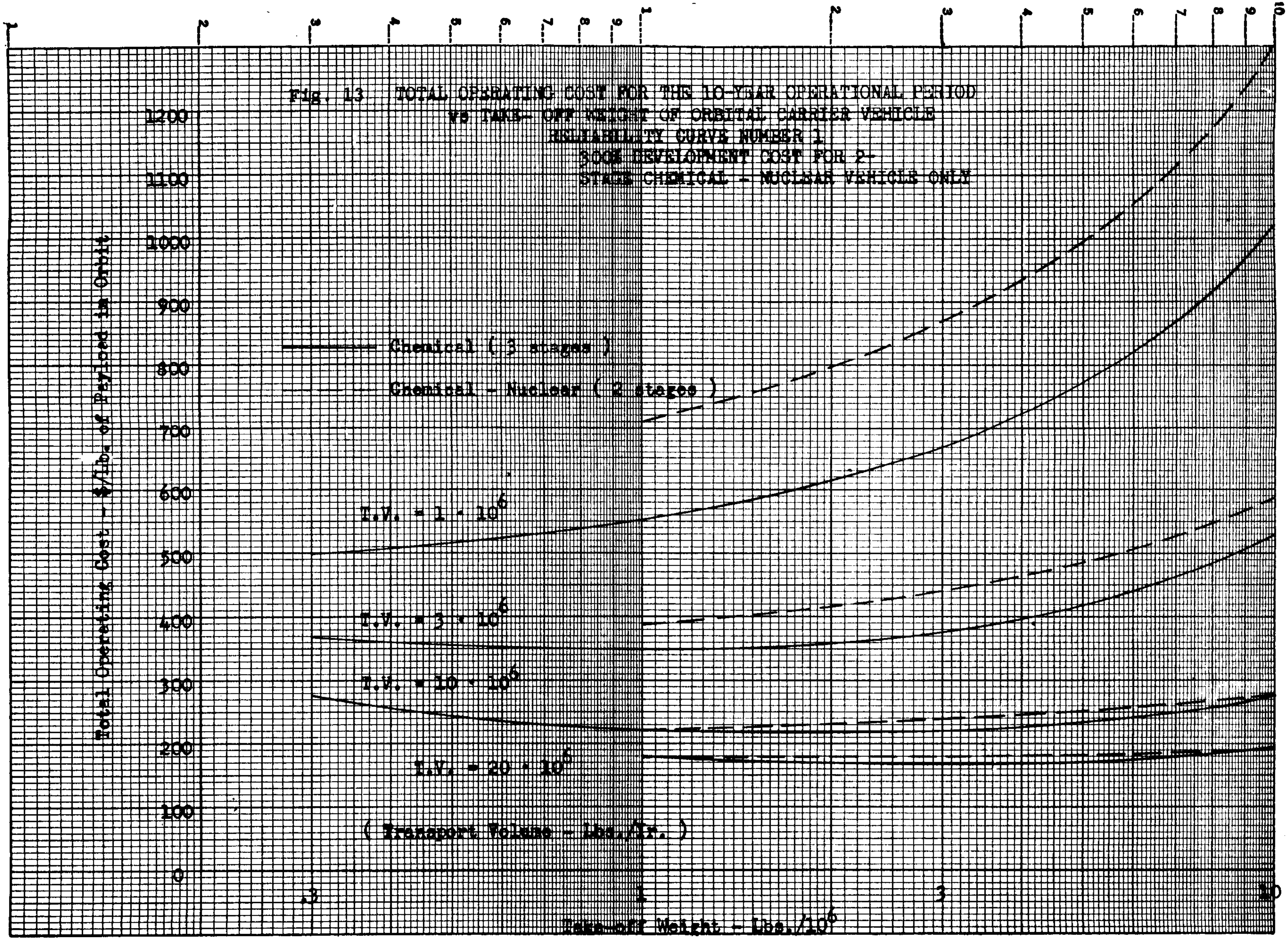


Fig. 13 TOTAL OPERATING COST FOR THE 10-YEAR OPERATIONAL PERIOD
vs TAKE- OFF WEIGHT OF ORBITAL CARRIER VEHICLE
RELIABILITY CURVE NUMBER 1
300% DEVELOPMENT COST FOR 2-
STAGE CHEMICAL - NUCLEAR VEHICLE ONLY

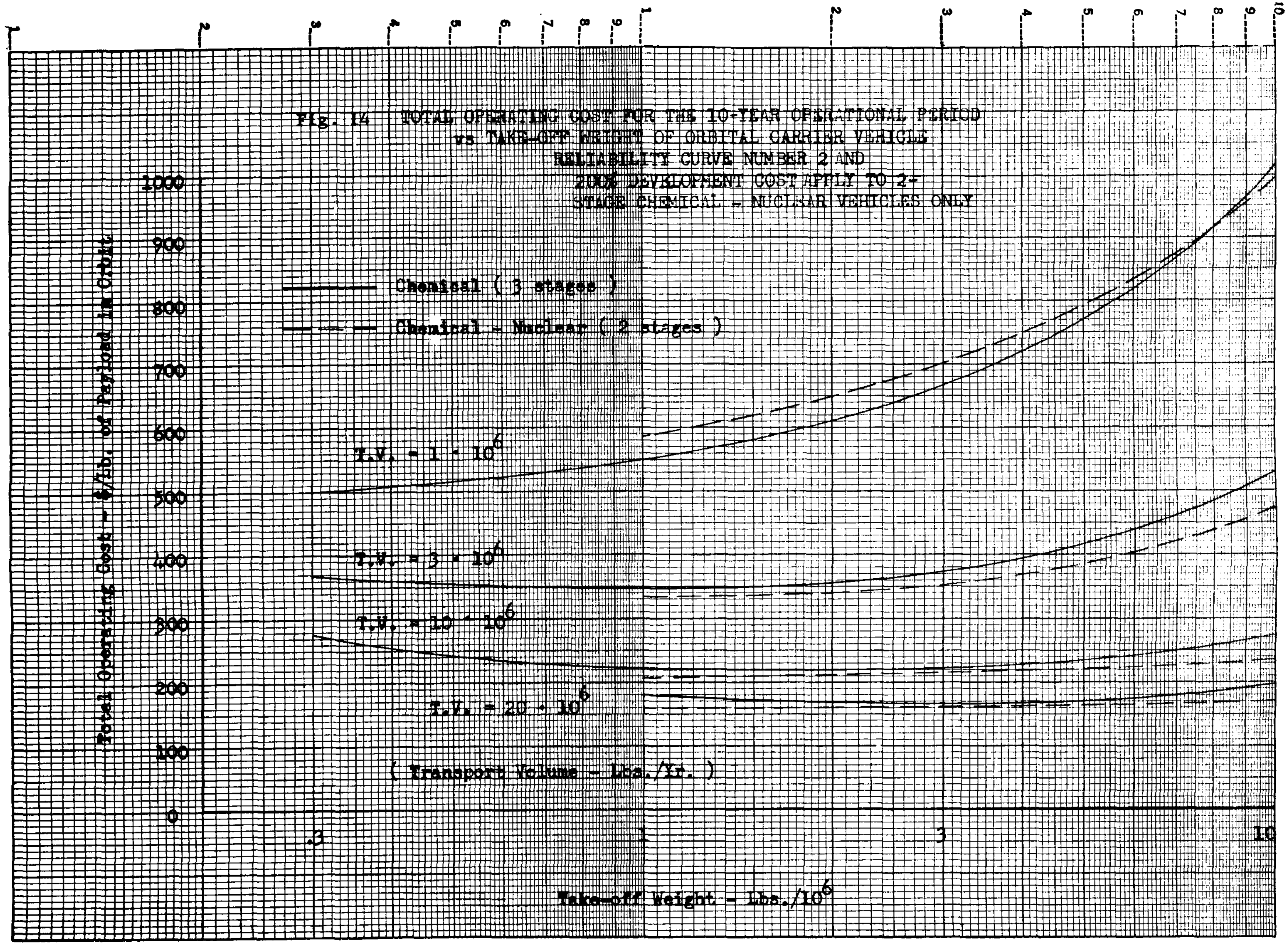


Fig. 14 TOTAL OPERATING COST FOR THE 10-YEAR OPERATIONAL PERIOD vs TAKE-OFF WEIGHT OF ORBITAL CARRIER VEHICLE RELIABILITY CURVE NUMBER 2 AND 200% DEVELOPMENT COST APPLY TO 2-STAGE CHEMICAL - NUCLEAR VEHICLES ONLY

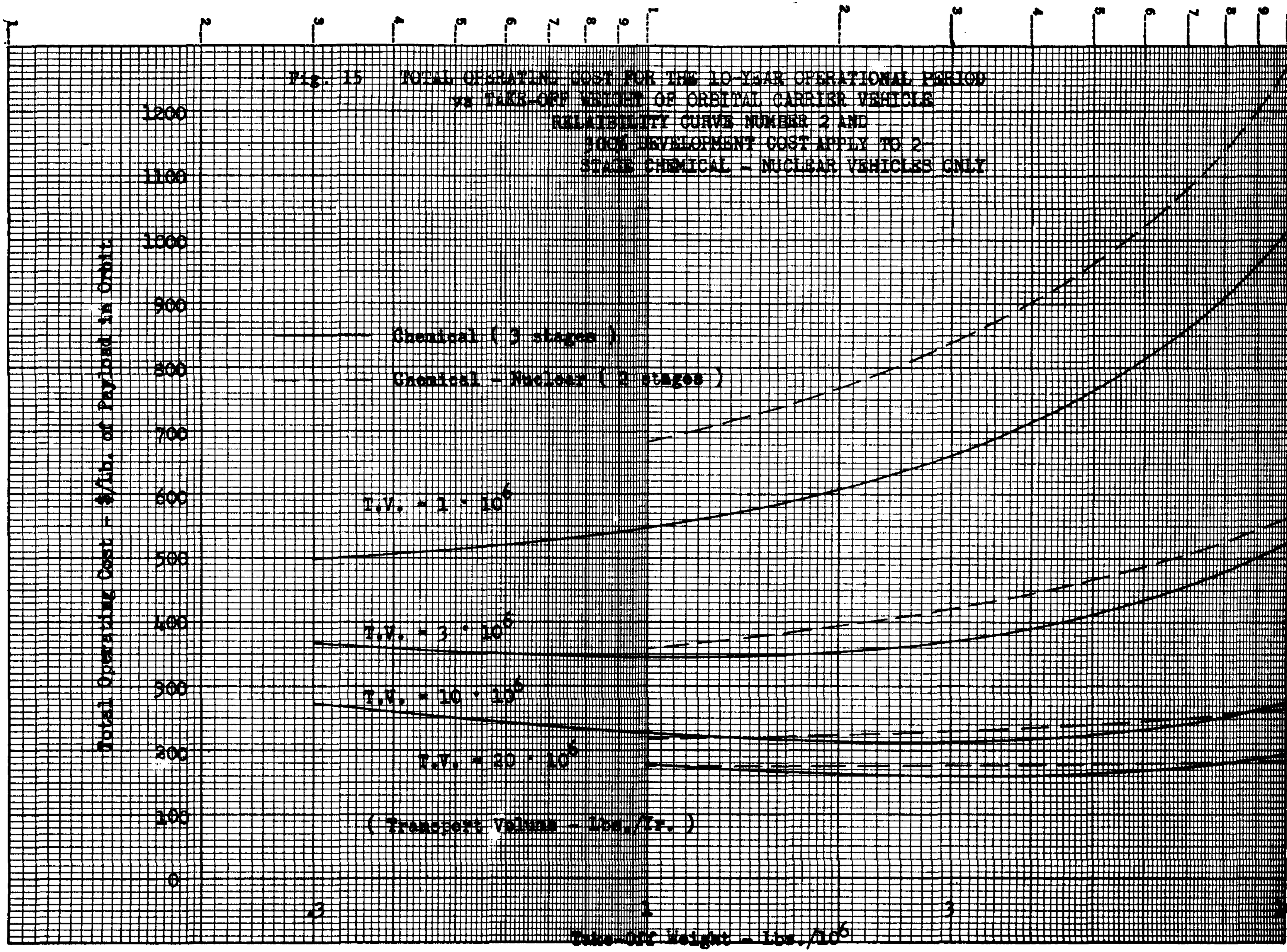


Fig. 15 TOTAL OPERATING COST FOR THE 10-YEAR OPERATIONAL PERIOD vs TAKE-OFF WEIGHT OF ORBITAL CARRIER VEHICLE
RELAIBILITY CURVE NUMBER 2 AND
300% DEVELOPMENT COST APPLY TO 2-STAGE CHEMICAL - NUCLEAR VEHICLES ONLY

Fig. 16 TOTAL OPERATING COST FOR THE 10-YEAR OPERATIONAL PERIOD vs TAKE-OFF WEIGHT OF ORBITAL CARRIER VEHICLE RELIABILITY CURVE NUMBER 3 AND 200% DEVELOPMENT COST APPLY TO 2-STAGE CHEMICAL - NUCLEAR VEHICLES ONLY

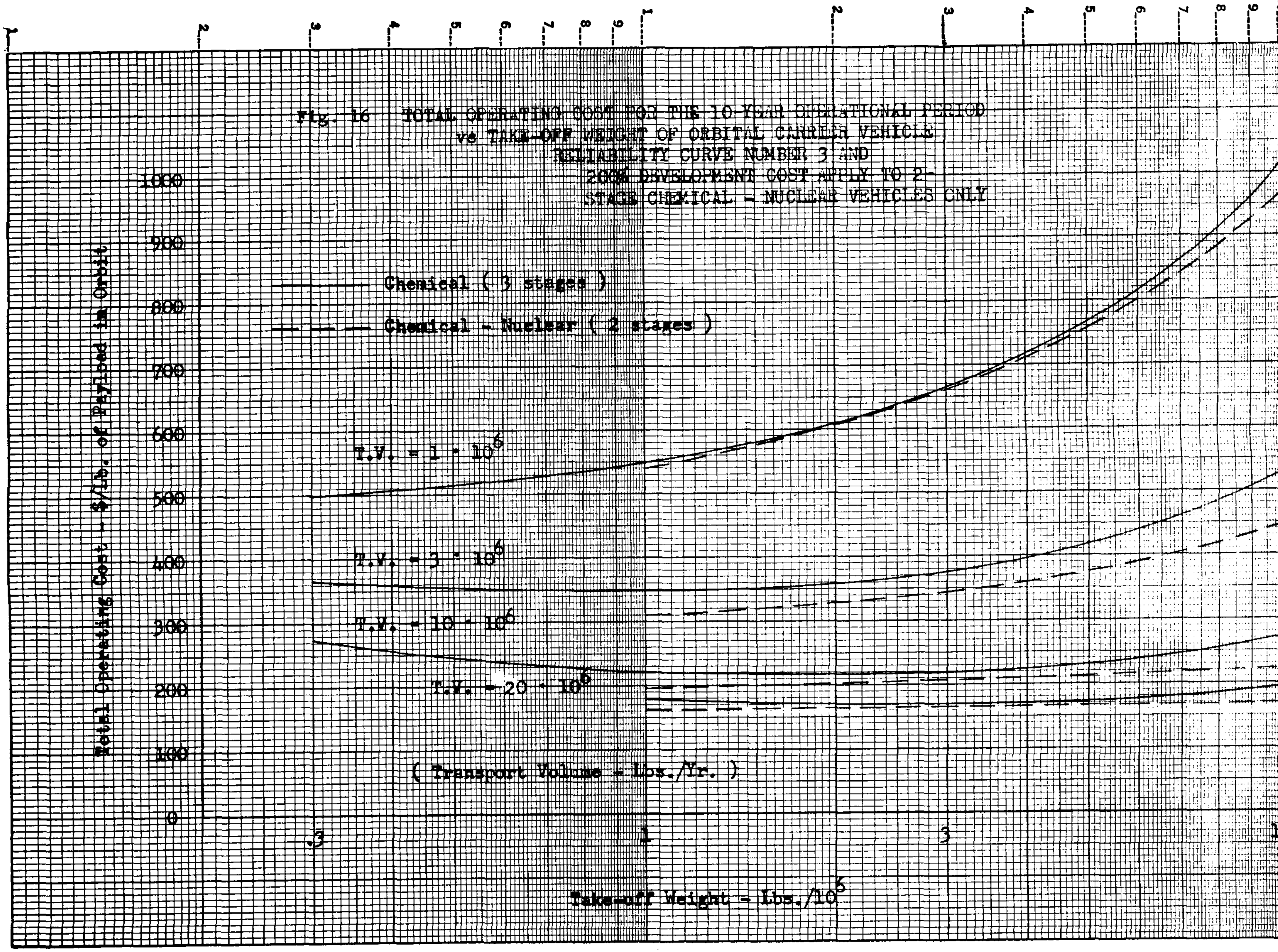
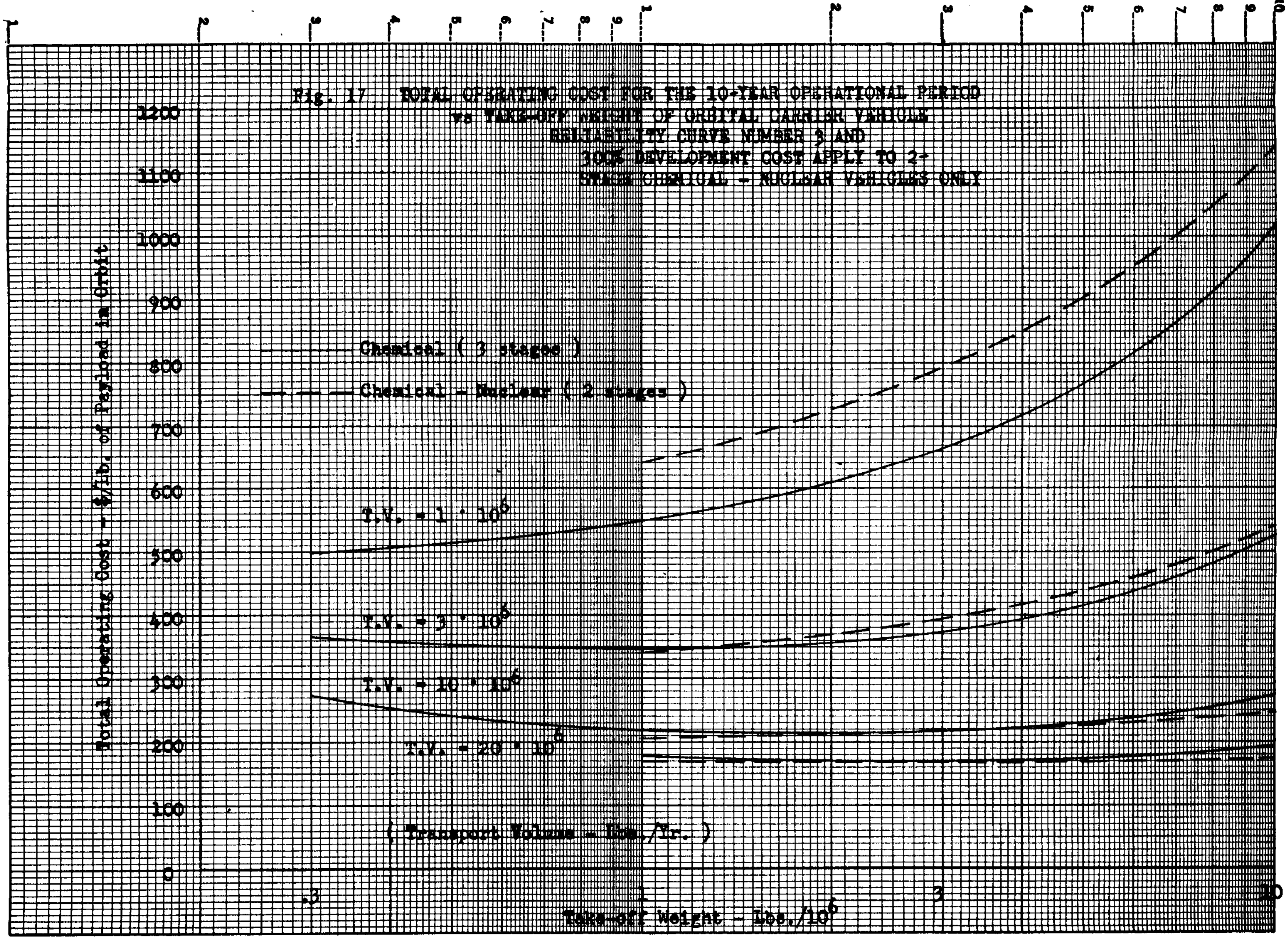


Fig. 17 TOTAL OPERATING COST FOR THE 10-YEAR OPERATIONAL PERIOD vs TAKE-OFF WEIGHT OF ORBITAL CARRIER VEHICLE RELIABILITY CURVE NUMBER 3 AND 300% DEVELOPMENT COST APPLY TO 2-STAGE CHEMICAL - NUCLEAR VEHICLES ONLY



APPENDIX I. LIST OF SYMBOLS

I_{sp}	Specific Impulse (sec)
W_o	Take-off Weight (lb)
W_c	Cutoff Weight (lb)
W_6	Unusable Propellants and Gas Residuals (lb)
W_7	Maximum Usuable Propellant Residuals (lb)
W_8	Expected Propellant Consumption (lb)
W_s	Dry Structure Weight (lb)
W_1	Total Payload (lb)
W_2	Vehicle Guidance and Control Equipment, Instrumentation (lb)
W_3	Fuselage and Equipment (lb)
W_4	Propulsion System and Accessories (lb)
M	W_o/W_1 - Growth Factor
T.V.	Annual Transport Volume (Weight of payloads per year transported into orbit - lb/yr)
C_L	Launch Operations Cost ($ per launch)
t	Pad Time per Launch (days)
N	Annual Firing Rate
a_c	Fixed Cost, Three-stage Chemical Vehicle ($)
a_n	Fixed Cost, Two-stage Chemical-Nuclear Vehicle ($)
b	Correction Factor

C_R	Range Cost ($ per launch)
$\left(C_G + C_F\right)_c$	Ground Support Equipment and Facility Cost, Three-stage Chemical Vehicle ($ per launch pad)
$\left(C_G + C_F\right)_n$	Ground Support Equipment and Facility Cost, Two-stage Chemical-Nuclear Vehicle ($ per launch pad)
R&D	Research and Development
GSE	Ground Support Equipment

APPENDIX II. COMPUTATIONAL METHOD

1. Vehicle Production Costs - The variation of production cost versus accumulated production number is shown in Figure 2 with time as a parameter. This figure is plotted for a unit dry weight of 100,000 lb. A correction factor for weights other than 100,000 lb is given as the lower curve in Figure 3.

2. Propellant Costs - The propellants are assumed to cost \$0.03/lb for LOX/RP, \$0.20/lb for LOX/H_2, and \$8000/lb for nuclear fuel. It is assumed that liquid H_2 will cost \$0.20/lb when used used with a nuclear stage.

3. Vehicle Transportation Costs - The average transportation cost is assumed to be \$1/lb for that weight transported a distance of 1000 miles.

4. Launch Operations Cost - The cost covering checkout, pad operation, and actual launching is assumed to be given by:

$$C_L = \frac{t \cdot N}{365}\left(a + b\sqrt{W_o}\right) \text{ \$ per launch}$$

where

$$t = \frac{100}{N} + \frac{\sqrt[3]{W_o}}{Y} \quad \text{(pad time per launch)}$$

$$a_c = 5 \cdot 10^6 \quad \text{(fixed cost, three-stage chemical vehicle)}$$

$$a_n = 10 \cdot 10^6 \quad \text{(fixed cost, two-stage chemical-nuclear vehicle)}$$

$$b = 10^4 \quad \text{(correction factor)}$$

5. Direct Operating Costs - The summation of production, propellant, transportation, and launch operation costs gives a direct operating cost.

6. Range Costs - The costs pertaining to the flight test range (also needed for operational flights) are estimated by the use of the following equation:

$$C_R = \left(0.2 + \frac{2.4}{N}\right) 10^6 \text{ \$ per launch}$$

7. Ground Support Equipment and Facility Costs - The costs chargeable to ground support equipment and facilities are calculated from:

$$\left(C_G + C_F\right)_c = 2\left(10\cdot 10^6 + 10^4\sqrt{W_o}\right)\ \$ \text{ (three-stage chemical vehicle)}$$

$$\left(C_G + C_F\right)_n = 2\left(15\cdot 10^6 + 10^4\sqrt{W_o}\right)$$

$ (two-stage chemical-nuclear vehicle)

This gives a cost per launch pad.

8. Development Costs - The costs of the vehicle development program are given by the upper curve of Figure 3 for the three-stage chemical vehicle. The development costs peculiar to the two-stage chemical-nuclear vehicle are given by the following:

Take-off weight (million lb)	1.2	2.4	10
Engine cost (million $)	150	250	400
Reactor cost (million $)	150	160	250
R&D GSE cost (million $)	150	175	200
Total (million $)	450	585	850

9. Indirect Operating Costs - Range costs, ground support equipment and facility costs, and development costs make-up the indirect operating costs.

10. Reliability Considerations - With the exception of development, each of the above costs will be increased by an assumed reliability factor. Using a given reliability curve, the required number of vehicles per year for a desired transport volume is obtained by iteration. The launch rate, in turn, affects the launch pad requirement. These assumed reliability factors are shown as a function of accumulated launches in Figure 1.

11. Average Operating Costs - After the individual costs have been adjusted for an assumed mission reliability, a cost per pound of payload into orbit can be determined. The total operating cost for a program divided by the amount of payload delivered gives an average specific total operating cost in $/lb for the carrier vehicles. The payload costs are not considered in this study.

REFERENCE

H. H. Koelle, On the Optimum Size of Orbital Carrier Vehicles Based on Over-all Economy, Presented to the 11th International Astronautical Congress of the International Astronautical Federation, Stockholm, Sweden, August 15-30, 1960

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